

Resonant production of leptogluons at the FCC based lepton-hadron colliders

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Abstract

Resonant production of leptogluons at the FCC based ep and μ p colliders have been analyzed. It is shown that e-FCC and μ -FCC will cover much wider region of e_8 and μ_8 masses than the LHC. While leptogluons with appropriate masses (if exist) will be discovered earlier by the FCC pp collider, lepton-proton colliders will give opportunity to handle very important additional information. For example, compositeness scale can be probed up to multi-hundred TeV region.

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I. INTRODUCTION

Color octet leptons are predicted by preonic models (see [1] and references therein) with colored preons (see, for example, fermion-scalar models [2, 3]). From phenomenological viewpoint their status is similar to that of excited leptons and leptoquarks. Concerning experimental searches situation is quite different: excited leptons and leptoquarks occupy an important place in the research program of almost all collider experiments, however, this is not the case for leptogluons (see Chapter titled “Quark and Lepton Compositeness, Search for” in [4] and references therein).

As for the phenomenological studies at TeV colliders: pair production of leptogluons at the LHC have been considered in [3, 5–7]. Resonant production of color octet electrons at the LHC based ep colliders is analyzed in [8–10]. In [11] indirect manifestations of color octet electrons at ILC and CLIC have been considered. Resonant production of color octet muons at muon collider based pp colliders was considered in [12]. It is interesting that color octet neutrinos may be the source of the IceCube PeV events [13].

Experimental bound on l_8 mass presented in [4], namely, $m_{l_8} > 86$ GeV is based on 25 years old CDF search for pair production of unit-charged particles which leave the detector before decaying [14]. As mentioned in [15] DO clearly exclude 200 GeV leptogluons decaying within the detector and could naively place the constraint $m_{l_8} > 325$ GeV. The twenty years old H1 search for color octet electron has excluded the compositeness scale $\Lambda < 3$ TeV for $m_{e_8} \approx 100$ GeV and $\Lambda < 240$ GeV for $m_{e_8} \approx 250$ GeV [16, 17]. While the LEP experiments did not perform dedicated search for leptogluons, low limits for excited lepton masses, namely 103.2 GeV [4], certainly is valid for color octet leptons, too. Finally, reconsideration of CMS results on leptoquark searches performed in [6] leads to the strongest limit $m_{e_8} > 1.2\text{--}1.3$ TeV.

In this paper we analyze the potential of the FCC [18] based ep and μ p colliders for charged leptogluon search. In Section II we present main parameters of the FCC based lepton-hadron colliders. Phenomenology of leptogluons is given in Section III. Resonant production of color octet electrons at e-FCC and color octet muons at μ -FCC is analysed in Sections IV and V, respectively. In section VI achievable values of compositeness scale are presented. Finally, section VII contains summary of obtained results.

II. FCC BASED ep AND μp COLLIDERS

FCC is future 100 TeV center-of-mass (CM) energy pp collider proposed at CERN and supported by European Union within the Horizon 2020 Framework Programme for Research and Innovation. It includes also an electron-positron collider options at the same tunnel (TLEP), as well as ep collider options. Construction of future e^+e^- colliders (or special e-linac) and $\mu^+\mu^-$ colliders tangential to FCC will give opportunity to achieve highest CM energies in ep and μp collisions. CM energy and luminosity values for different options are given in Table 1.

Table I: Main parameters of the FCC based lepton-hadron colliders [19]

Collider name	E_l , TeV	\sqrt{s} , TeV	$L_{int} = fb^{-1}(\text{per year})$
ERL60-FCC	0.06	3.46	100
FCC-e80	0.08	4.00	230
FCC-e120	0.12	4.90	120
FCC-e175	0.175	5.92	40
OPL500-FCC	0.5	10.0	10 - 100
OPERL500-FCC	0.5	10.0	100 - 300
OPL1000-FCC	1	14.1	5 - 50
OPERL1000-FCC	1	14.1	50 - 150
OPL5000-FCC	5	31.6	1 - 10
OPERL5000-FCC	5	31.6	10 - 30
$\mu 63$ -FCC	0.063	3.50	0.1 - 1
$\mu 175$ -FCC	0.175	5.92	2 - 20
$\mu 750$ -FCC	0.75	12.2	5 - 50
$\mu 1500$ -FCC	1.5	17.3	5 - 50
$\mu 3000$ -FCC	3	24.5	10 - 100

In Table 1 ERL60 denotes conventional energy recovery; e80, e120 and e175 denote e-ring in the FCC tunnel; OPL denotes one pass linac tangential to the FCC; OPERL denotes adding second (decelerating) linac shoulder for energy recovery. Last 5 rows denote construction of μ -rings tangential to the FCC (for details see [19]).

III. COLOR OCTET LEPTONS

Following reference [3] we assume that preons are color triplets and follow usual statistics (Fermi-Dirac for fermions and Bose-Einstein for bosons), which means that SM fermions should contain odd number of fermionic preons. In fermion-scalar models leptons are bound states of one fermionic preon and one scalar anti-preon

$$l = (F\bar{S}) = 1 + 8 \quad (1)$$

therefore, each SM lepton has one color octet partner. In three-fermion models the color decomposition is

$$l = (FFF) = 1 + 8 + 8 + 10 \quad (2)$$

therefore, each SM lepton has two color octet and one color decuplet partners. As for quark sector, each SM quark has anti-sextet partner in fermion-scalar models (anti-triplet, anti-sextet and 15-plet partners in three-fermion models).

Concerning the relation between compositeness scale and masses of leptogluons, two scenarios can be considered: $m_{l_8} \approx \Lambda$ (QCD-like scenario) and $m_{l_8} \ll \Lambda$ (Higgs-like scenario). In the second scenario SM-like hierarchy may be realized, namely, $m_{e_8} \ll m_{\mu_8} \ll m_{\tau_8} \ll \Lambda$. Hereafter, numerical calculations will be performed for $\Lambda = m_{l_8}$ and $\Lambda = 100$ TeV cases.

For the interaction of leptogluons with the corresponding lepton and gluon we use the following Lagrangian [4, 9]:

$$L = \frac{1}{2\Lambda} \sum_l \left\{ \bar{l}_g^\alpha g_s G_{\mu\nu}^\alpha \sigma^{\mu\nu} (\eta_L l_L + \eta_R l_R) + h.c. \right\} \quad (3)$$

where $G_{\mu\nu}^\alpha$ is the field strength tensor for gluon, index $\alpha = 1, 2, \dots, 8$ denotes the color, g_s is Gauge coupling, η_L and η_R are the chirality factors, l_L and l_R denote left and right spinor components of lepton, $\sigma^{\mu\nu}$ is the antisymmetric tensor and Λ is the compositeness scale. The leptonic chiral invariance implies $\eta_L \eta_R = 0$. For numerical calculations we add leptogluons into the CalcHEP program [20].

Decay width of the color octet lepton is given by

$$\Gamma(l_8 \rightarrow l + g) = \frac{\alpha_s M_{l_8}^3}{4\Lambda^2} \quad (4)$$

In Fig. 1 the decay width of leptogluons are presented for two scenarios, namely, $\Lambda = m_{l_8}$ and $\Lambda = 100$ TeV. The resonant l_8 production cross sections for different options of the FCC based lp colliders (Table I), evaluated using CalcHEP with CTEQ6L parametrization [21] for parton distribution functions, are presented in Figs. 2 and 3 (for $\Lambda = m_{l_8}$ and $\Lambda = 100$ TeV, respectively). At this stage we ignore beamstrahlung effects, which leads to reduction of cross sections at ep colliders (see next section).

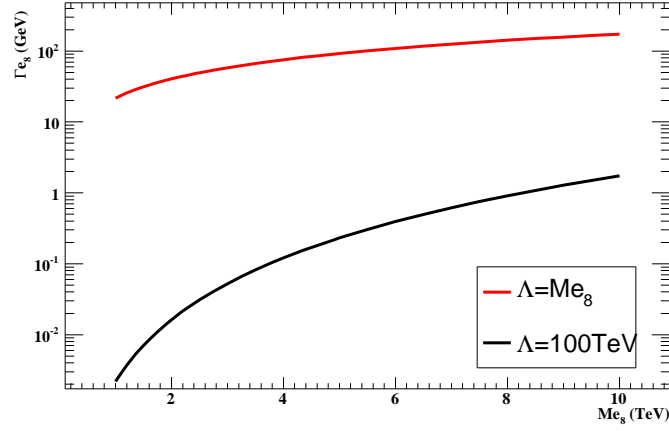


Figure 1: Leptogluon decay width vs its mass for $\Lambda = m_{l_8}$ and $\Lambda = 100$ TeV.

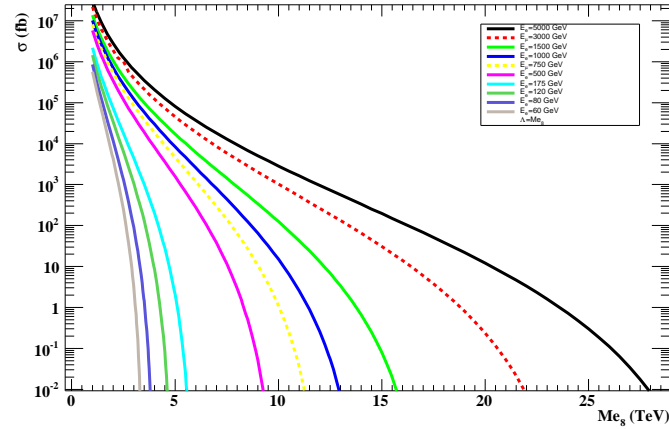


Figure 2: Resonant l_8 production at the FCC based lp colliders for $\Lambda = m_{l_8}$.

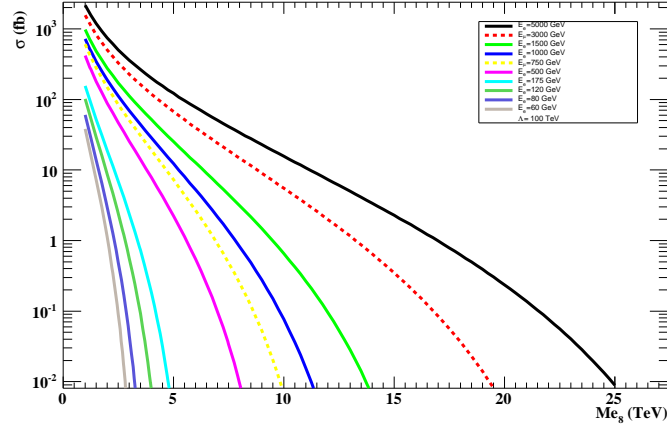


Figure 3: Same as Fig. 2 for $\Lambda = 100$ TeV.

IV. COLOR OCTET ELECTRONS AT THE FCC BASED EP COLLIDERS: SIGNAL VS BACKGROUND

In this case beamstrahlung reduces production cross-section of color octet electrons, especially at large m_{e8} values. This reduction is illustrated in Table 2 for ERL60-FCC. Analysis in this section is performed taking into account beamstrahlung effects using "beamstrahlung on" option for initial electron state in CalcHEP.

Table II: Effect of beamstrahlung at ERL60-FCC (cross-sections are given for $\Lambda = m_{e8}$)

m_{e8} , GeV	Cross-section, fb		Reduction
	Beamstrahlung on	Beamstrahlung off	
1000	3.59×10^5	3.87×10^5	0.93
2000	2.32×10^3	2.67×10^3	0.87
3000	6.49	7.66	0.85

In order to determine appropriate cuts we start with consideration of p_t and η distributions for signal and background processes. Numerical calculations are performed at the partonic level using CalcHEP simulation program [20] with CTEQ6L parton distribution functions [21] and generic cuts $p_t(e) > 30$ GeV, $p_t(j) > 50$ GeV, where j means gluon for signal and quarks for background processes. Main contributions to the background came from

lepton-quark scatterings via photon and Z-boson exchange.

Transverse momentum distributions of final state jets for signal (with $\Lambda = m_{e8}$) and background are shown in Fig. 4. Let us mention that same distributions are valid for final electrons, too. It is seen that $p_t > 400$ GeV cut essentially reduces background, whereas signal is almost unaffected (especially for large m_{e8} values). Below we use $p_t(e) > 400$ GeV, $p_t(j) > 400$ GeV as a discovery cut for all ep colliders, keeping in mind $m_{e8} > 1.2$ TeV from the LHC $\sqrt{s} = 8$ TeV data [6]. Pseudo-rapidity distributions for final electrons and jets are presented in Figs. 5 and 6, respectively. Corresponding discovery cuts for different ep collider options are given in Table 3.

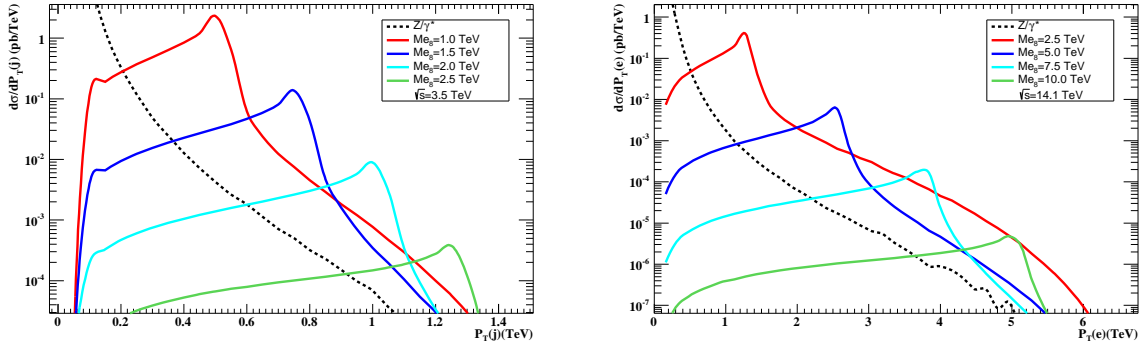


Figure 4: Transverse momentum distributions of final state jets (and electrons) for signal and background at ERL60-FCC (left) and OPL1000-FCC (right).

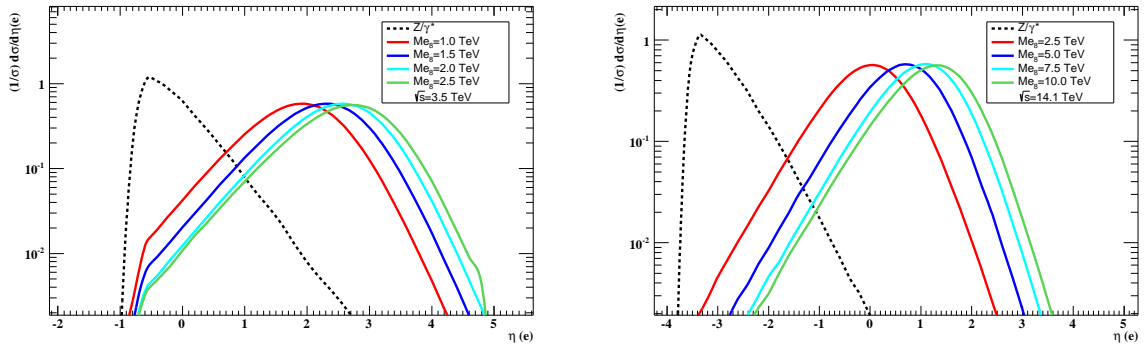


Figure 5: Normalized pseudo-rapidity distributions of final electrons for signal and background at ERL60-FCC (left) and OPL1000-FCC (right).

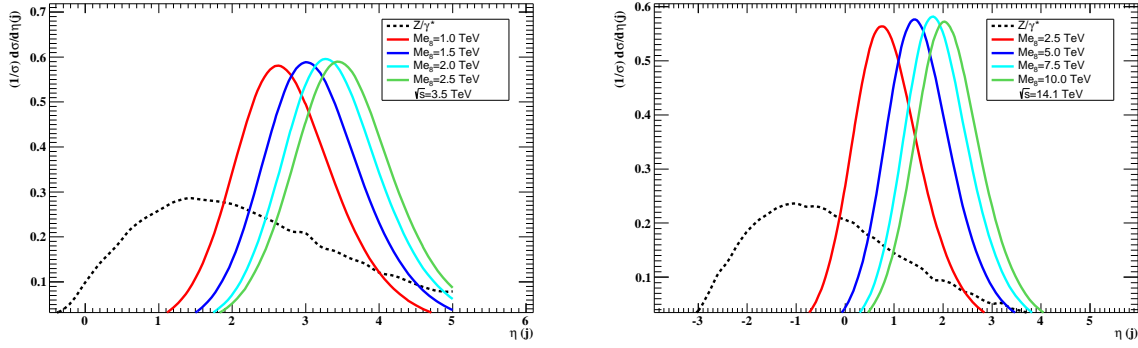


Figure 6: Normalized pseudo-rapidity distributions of final jets for signal and background at ERL60-FCC (left) and OPL1000-FCC (right).

Table III: Pseudorapidity cuts for different ep collider options

Electron Energy, GeV	60	175	500	1000
η_e	$1 < \eta_e < 4$	$0 < \eta_e < 4$	$-1 < \eta_e < 4$	$-1.5 < \eta_e < 4$
η_j	$2 < \eta_j < 4$	$1 < \eta_j < 4$	$0 < \eta_j < 4$	$-0.5 < \eta_j < 4$

In Table 4 we present observation (3σ) and discovery (5σ) limits on masses of color octet electrons for different FCC based ep collider options. For statistical significance we use

$$S = \frac{\sigma_s}{\sqrt{\sigma_s + \sigma_b}} \sqrt{L_{int}} \quad (5)$$

where σ_s (σ_b) means signal (background) cross section and L_{int} is integrated luminosity. With the pair production channel, the 14 TeV LHC can probe color octet electrons with masses up to 2.5 TeV with 100 fb⁻¹ of integrated luminosity [5]. It is seen that FCC based ep colliders cover essentially wider region of e_8 's mass.

Table IV: Observation (3σ) and discovery (5σ) limits for color octet electrons

Collider Name	Λ	L_{int}, fb^{-1}	m_{e_8}, GeV	
			3σ	5σ
ERL60-FCC $\sqrt{s} = 3.46 \text{ TeV}$	m_{e_8}	10	2990	2900
		100	3150	3085
	100 TeV	10	1150	-
		100	1690	1485
FCC-e175 $\sqrt{s} = 5.92 \text{ TeV}$	m_{e_8}	40	5110	4970
	100 TeV	40	2675	2350
OPL500-FCC $\sqrt{s} = 10.0 \text{ TeV}$	m_{e_8}	10	7825	7500
		100	8450	6600
	100 TeV	10	3800	3200
		100	5070	4520
OPL1000-FCC $\sqrt{s} = 14.1 \text{ TeV}$	m_{e_8}	5	10200	9640
		50	11220	10800
	100 TeV	5	5000	4100
		50	6750	6000

V. COLOR OCTET MUONS AT THE FCC BASED μP COLLIDERS: SIGNAL VS BACKGROUND

For illustration we consider $\mu 750\text{-FCC}$. Transverse momentum distributions of final state muons for signal (with $\Lambda = m_{e_8}$) and background are shown in Fig. 7. Let us remind that same distributions are valid for final state jets, too. Similar to ep case, we use $p_t(\mu) > 400 \text{ GeV}$, $p_t(j) > 400 \text{ GeV}$ as a discovery cut for all μp colliders (rough estimations show that color octet muons with masses below 1 TeV are excluded by the LHC $\sqrt{s} = 8 \text{ TeV}$ data). Pseudo-rapidity distributions for final muons and jets are presented in Figs. 8 and 9, respectively. Corresponding discovery cuts for different μp collider options are given in Table 5.

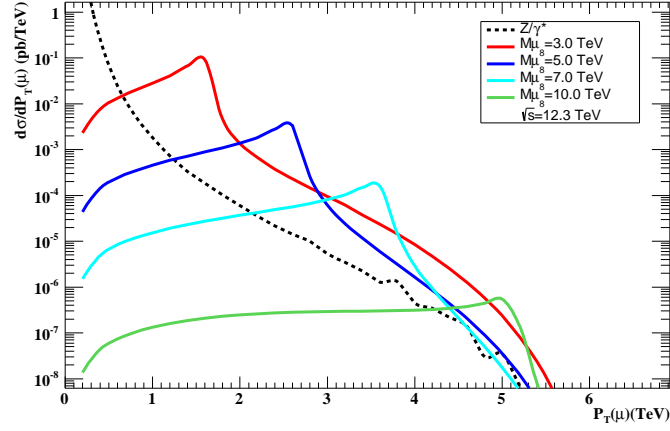


Figure 7: Transverse momentum distributions of final state muons (and jets) for signal and background at $\mu 750$ -FCC.

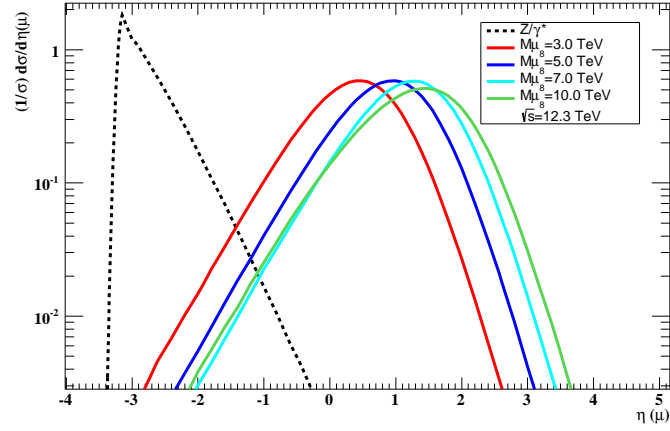


Figure 8: Normalized pseudo-rapidity distributions of final muons for signal and background at $\mu 750$ -FCC.

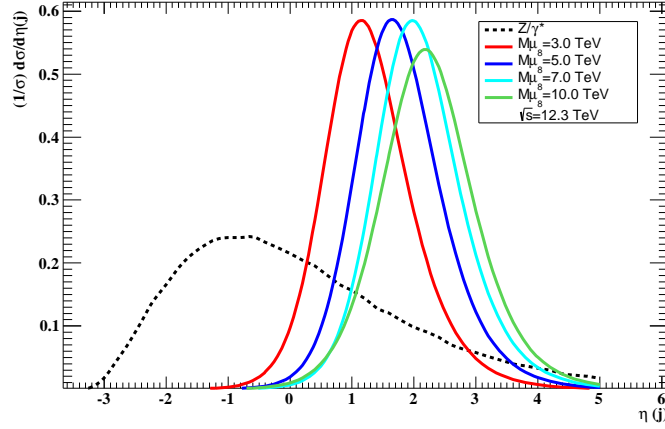


Figure 9: Normalized pseudo-rapidity distributions of final jets for signal and background at $\mu 750$ -FCC.

Table V: Pseudorapidity cuts for different μp collider options

Muon Energy, GeV	63	175	750
η_μ	$1 < \eta_\mu < 4$	$0 < \eta_\mu < 4$	$-1 < \eta_\mu < 4$
η_j	$2 < \eta_j < 4$	$1 < \eta_j < 4$	$0 < \eta_j < 4$

In Table 6 we present observation (3σ) and discovery (5σ) limits on masses of color octet muons for different FCC based μp collider options. Again FCC based μp colliders cover essentially wider region of μ_8 's mass comparing to the LHC.

Table VI: Observation (3σ) and discovery (5σ) limits for color octet muons

Collider Name	Λ	L_{int}, fb^{-1}	m_{μ_8}, GeV	
			3σ	5σ
$\mu 63\text{-FCC } \sqrt{s} = 3.50 \text{ TeV}$	m_{μ_8}	0.1	2580	2430
		1	2880	2760
	100 TeV	0.1	-	-
		1	-	-
$\mu 175\text{-FCC } \sqrt{s} = 5.92 \text{ TeV}$	m_{μ_8}	2	4700	4500
		20	5080	4930
	100 TeV	2	1450	-
		20	2230	1900
$\mu 750\text{-FCC } \sqrt{s} = 12.2 \text{ TeV}$	m_{μ_8}	5	9225	8780
		50	10060	9730
	100 TeV	5	3900	3200
		50	5350	4700

VI. COMPOSITENESS SCALE

Although the FCC based lp colliders will cover much wider m_{l_8} mass regions than LHC, this is not the case for the FCC pp option: rough estimations show that FCC-pp will give opportunity to discover color octet leptons up to 20 TeV mass values. In this section we analyze potential of e-FCC and μ -FCC for determination of compositeness scale. While the knowledge of color octet electron (and/or muon) mass will give opportunity to further optimization of cuts for purpose of Λ determination, in our analysis we use $p_t, \eta_e, \eta_j, \eta_\mu, m_{inv}(lj)$ cut values given in sections VI and V for e_8 and μ_8 , respectively. Achievable compositeness scales at the FCC based ep and μ p colliders are presented in Tables 7 and 8, respectively.

Table VII: Achievable compositeness scale in TeV units at the FCC based ep colliders.

ERL60-FCC	3σ		5σ	
	L=10 fb ⁻¹	L=100 fb ⁻¹	L=10 fb ⁻¹	L=100 fb ⁻¹
1000	100000	195000	85000	150000
1500	62000	105000	49000	82000
2000	32000	51000	26800	48000
2500	15000	27000	10000	20000
FCC-e175	3σ		5σ	
	L=40 fb ⁻¹			
1000	280000		210000	
2000	135000		122200	
3000	60000		47200	
4000	27500		21000	
OPL500-FCC	3σ		5σ	
	L=10 fb ⁻¹	L=100 fb ⁻¹	L=10 fb ⁻¹	L=100 fb ⁻¹
1000	363000	653000	277000	503000
3000	156250	283000	119000	218000
5000	57500	105500	43250	81000
7000	16750	32000	12000	24000
OPL1000-FCC	3σ		5σ	
	L=5 fb ⁻¹	L=50 fb ⁻¹	L=5 fb ⁻¹	L=50 fb ⁻¹
1000	255000	368000	191000	342000
2500	172500	295000	126000	228000
5000	67000	120000	52000	97000
7500	29000	54000	22000	41000
10000	11420	23000	7750	16750

Table VIII: Achievable compositeness scale in TeV units at the FCC based μp colliders.

FCC- $\mu 175$	3σ		5σ	
	L=2 fb $^{-1}$	L=20 fb $^{-1}$	L=2 fb $^{-1}$	L=20 fb $^{-1}$
1000	129000	234000	98000	180000
2000	66250	119250	50000	92000
3000	29750	54500	22250	41750
4000	13250	25750	9500	19250
$\mu 750$ -FCC	3σ		5σ	
	L=5 fb $^{-1}$	L=50 fb $^{-1}$	L=5 fb $^{-1}$	L=50 fb $^{-1}$
1000	264000	474000	203000	367000
3000	141000	254000	108000	196000
5000	63500	114500	48250	88250
7000	27500	50750	20750	39000
10000	4500	10750	1250	8000

VII. CONCLUSIONS

Certainly, if color octet leptons have mass values covered by the FCC based lp colliders, they will be observed earlier at the FCC pp option. Nevertheless, e-FCC and μ -FCC will give opportunity to obtain very important information which cannot be handled by the FCC-pp. As shown in section VI, compositeness scale well above 100 TeV can be probed. Very important feature of OPL-FCC ep colliders, namely, longitudinal polarization of electrons will give opportunity to determine the Lorentz structure of l_g -l-g vertex (the work on the subject is under progress). In general, lepton-hadron colliders has cleaner environment than hadron colliders. Finally, possible discovery of color octet leptons at the FCC-pp will determine the type of future lp collider to be installed.

Acknowledgments

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